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Time-Resolved Microscopic Imaging of Laser-Induced Material Modifications in Optical Materials

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Time-Resolved Microscopic Imaging of Laser-Induced Material
Modifications in Optical Materials
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Time-Resolved Microscopic Imaging of Laser-Induced Material Modifications in Optical Materials

Presentation to the
CLEO/QELS 2010 Conference

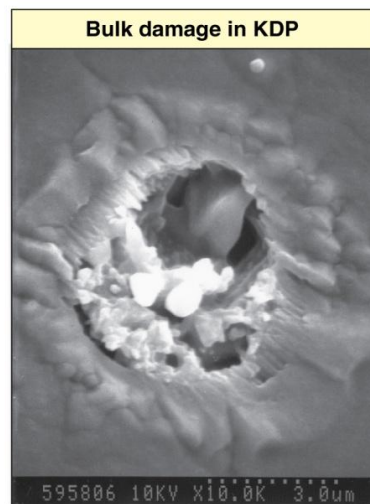


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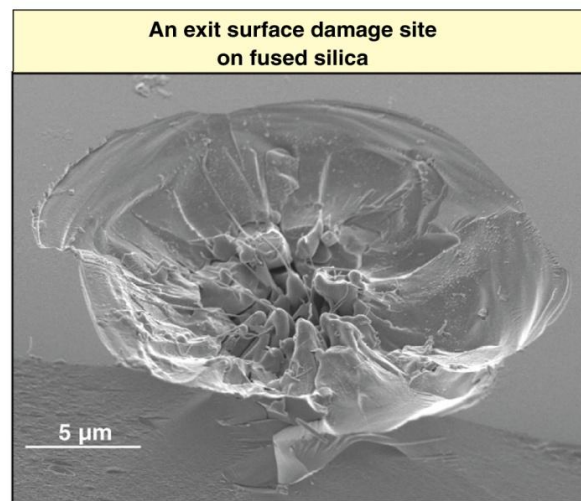
May 17, 2010

Motivation

- **Materials science problem: localized energy deposition → sequence of transient material modifications and formation of a void**
 - Energy coupling mechanisms
 - Solid state material response to localized extreme conditions
 - Energy transport through complex material phases
 - Material displacement and lattice transformation
- **Practical reasons:**
 - What causes and/or how to eliminate damage in optical components
 - How damage evolves (timeline)



Carr et al., APL, 89,
131901 (2006)



Wong et al., J. Non. Cryst. Solids, 352,
255 (2006)

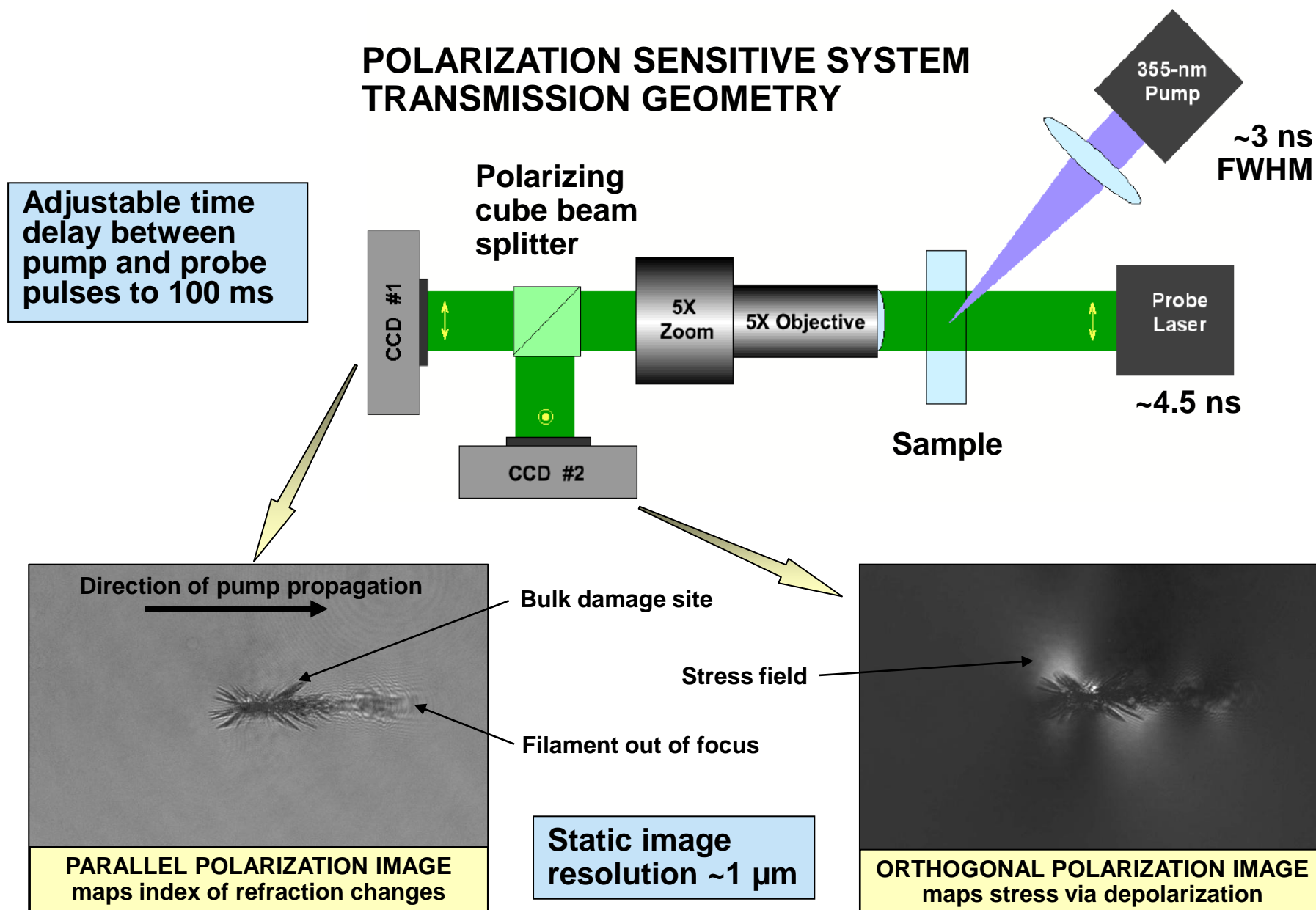
Objectives

- We want to elucidate the processes involved during a damage event in optical materials
 - Develop the experimental capabilities to measure the relevant processes with adequate resolution
 - Use experimental results to validate theoretical models

Today I will discuss the material response during the cooling phase in bulk fused silica following localized energy deposition via ns laser-induced breakdown

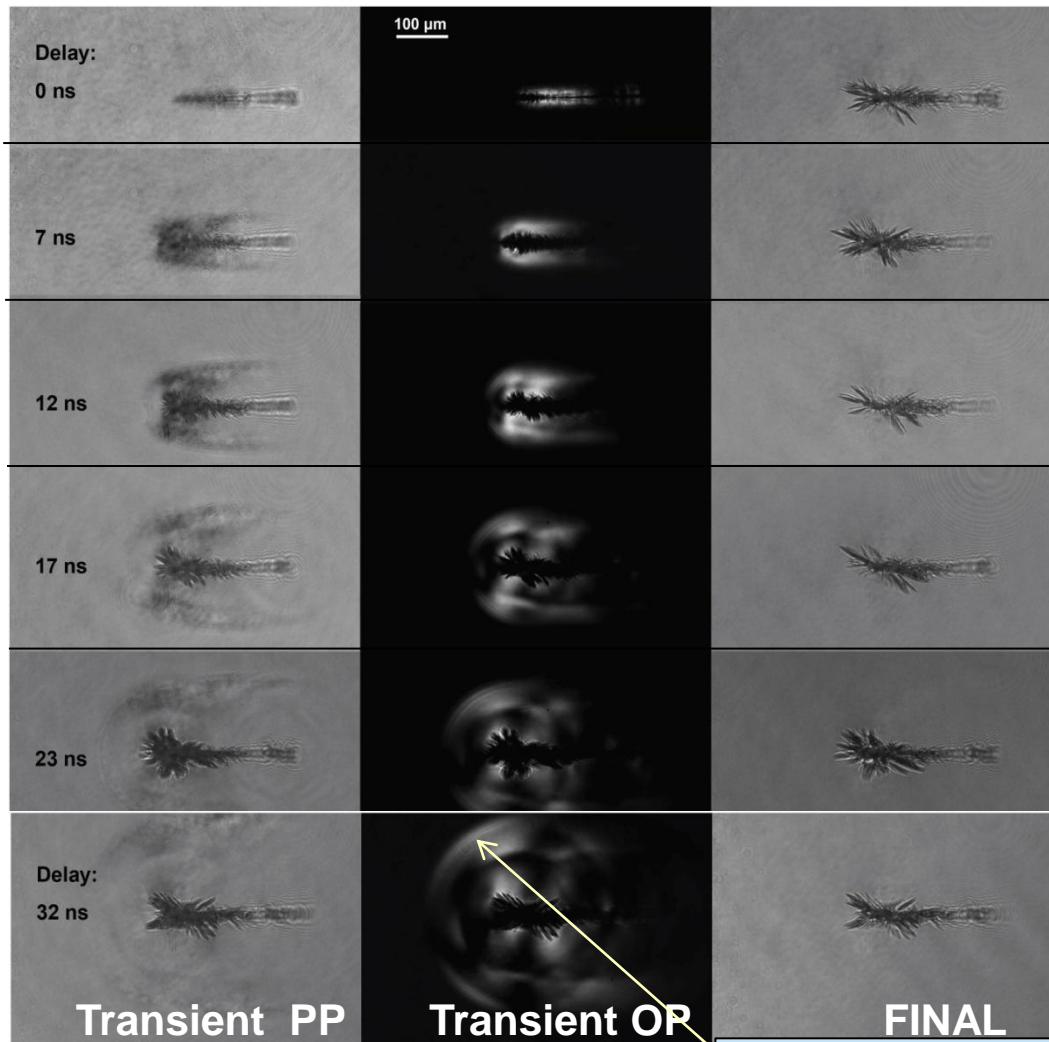
Time-resolved microscopy system is used to image the evolution of bulk damage in SiO₂

POLARIZATION SENSITIVE SYSTEM TRANSMISSION GEOMETRY

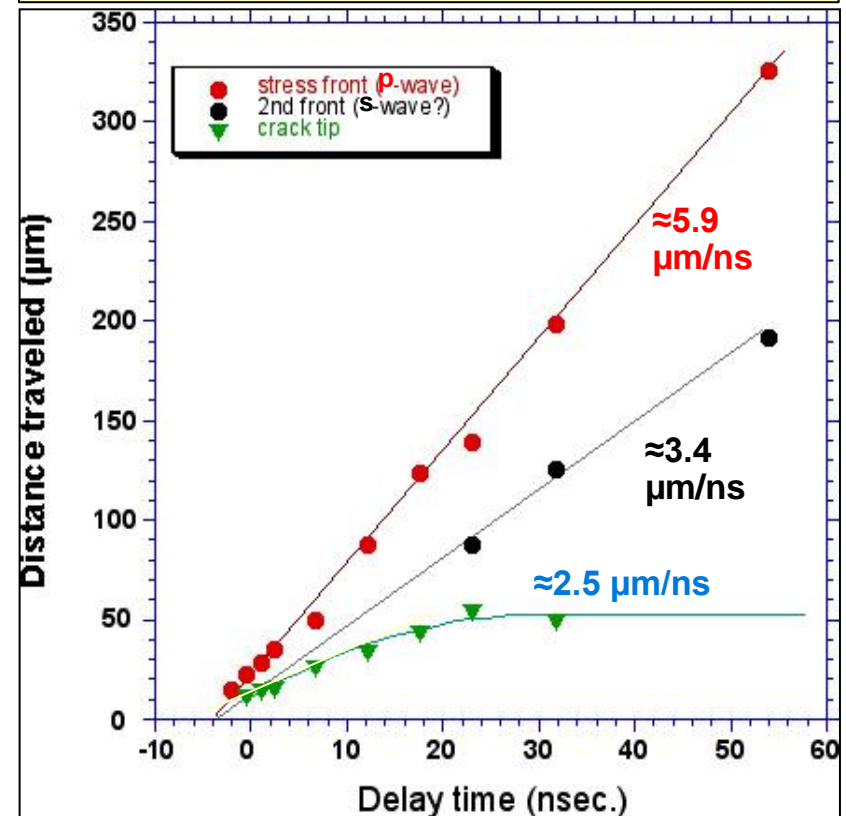


Images at different delays reveal the material response during the entire timeline of bulk damage

- 1) Shock fronts 2) Initiation and propagation of cracks
- 3) Transient absorption at crack and core regions 4) Return to solid phase



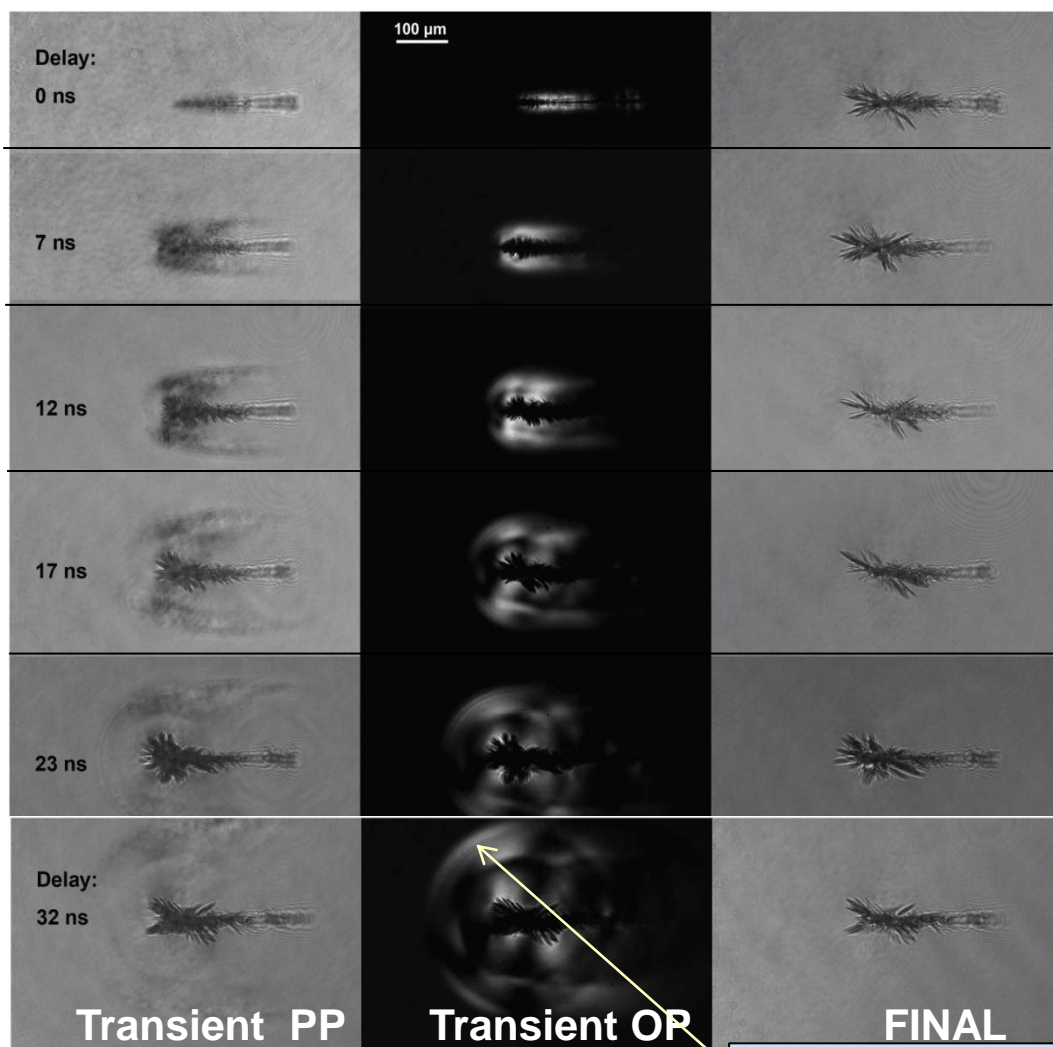
Dynamics of the main features observed during a bulk damage event



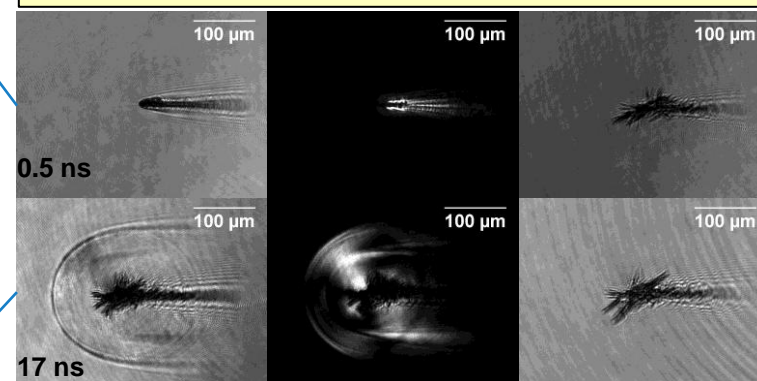
The spatial resolution of dynamic events was limited at the time by the pulse length of the probe pulse

Images at different delays reveal the material response during the entire timeline of bulk damage

- 1) Shock fronts 2) Initiation and propagation of cracks
- 3) Transient absorption at crack and core regions 4) Return to solid phase



Early dynamics can be resolved using a 150-ps probe laser

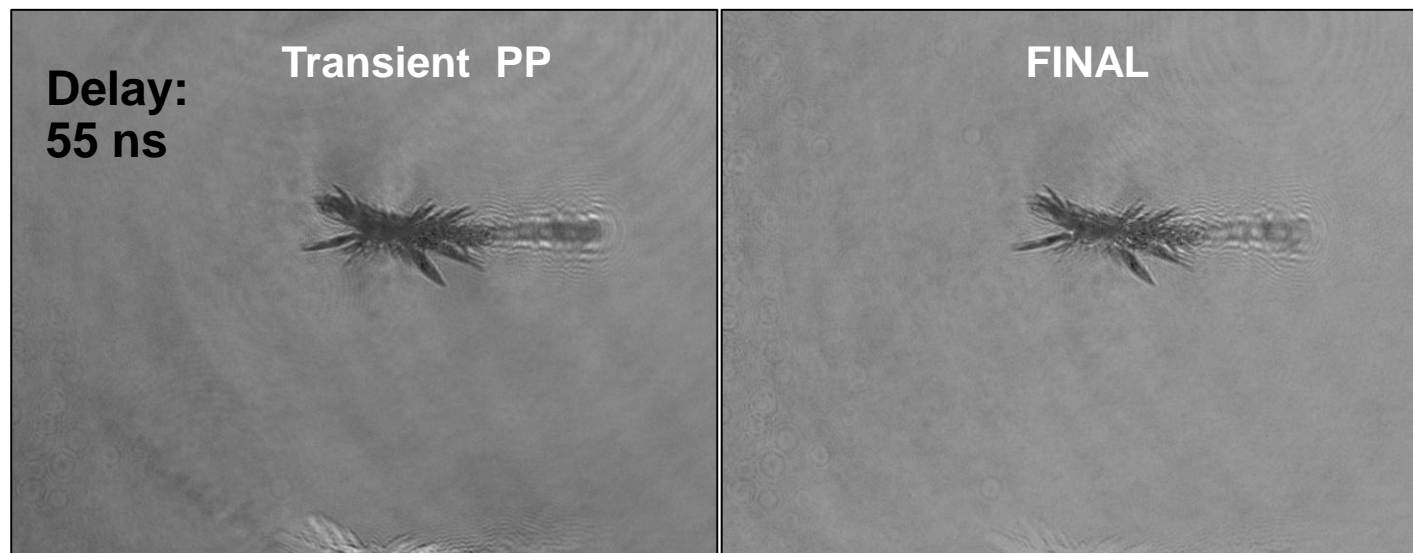


Modeling of ps-time resolved images of shock fronts, crack propagation and stress waves is currently underway (P. DeMange)

Limited spatial resolution of dynamic events (5-ns probe pulse -> 30 μm resolution)

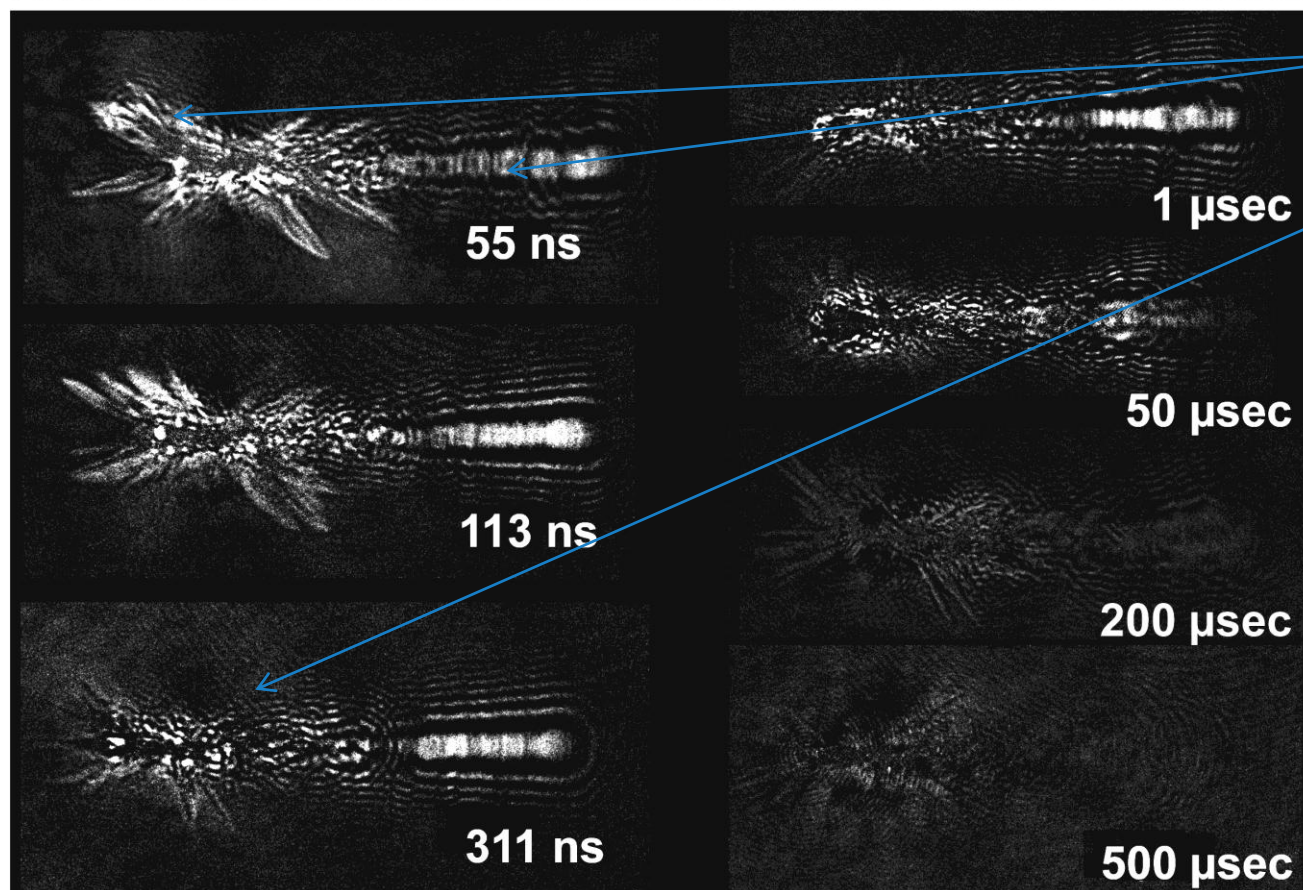
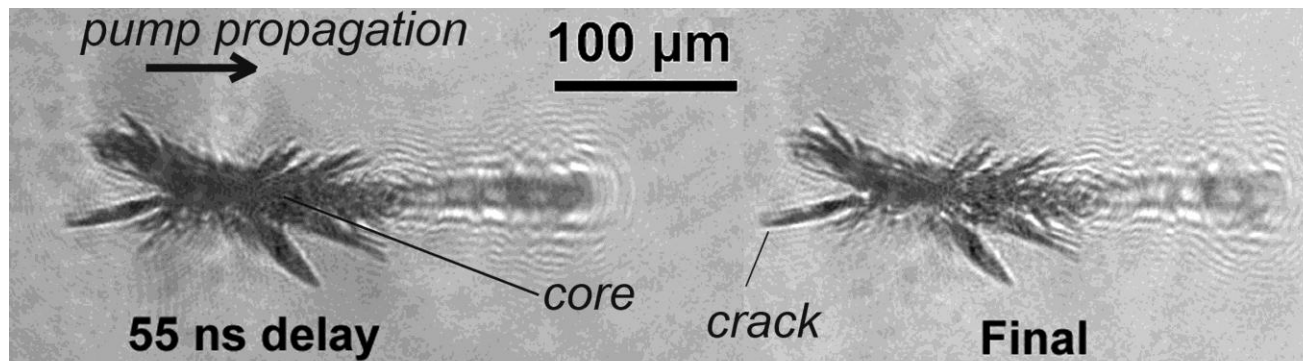
In the following, I will discuss the material response during the cooling phase

- 1) Shock fronts 2) Initiation and propagation of cracks
- 3) Transient absorption at crack and core regions 4) Return to solid phase



- Results suggest that crack growth proceeds up to ~30 ns delay
- At delays longer than ~50 ns, the transient overall dimensions of the damage site appear the same as the final
- However, the contrast between the transient and final images (in the parallel polarization) is different

Ratio TR (final/transient) images highlight the locations of the transient absorption



- Cracks and core region absorb light
- Absorption by cracks stops at ~ 300 ns

Ratio TR images highlight the locations of the transient absorption

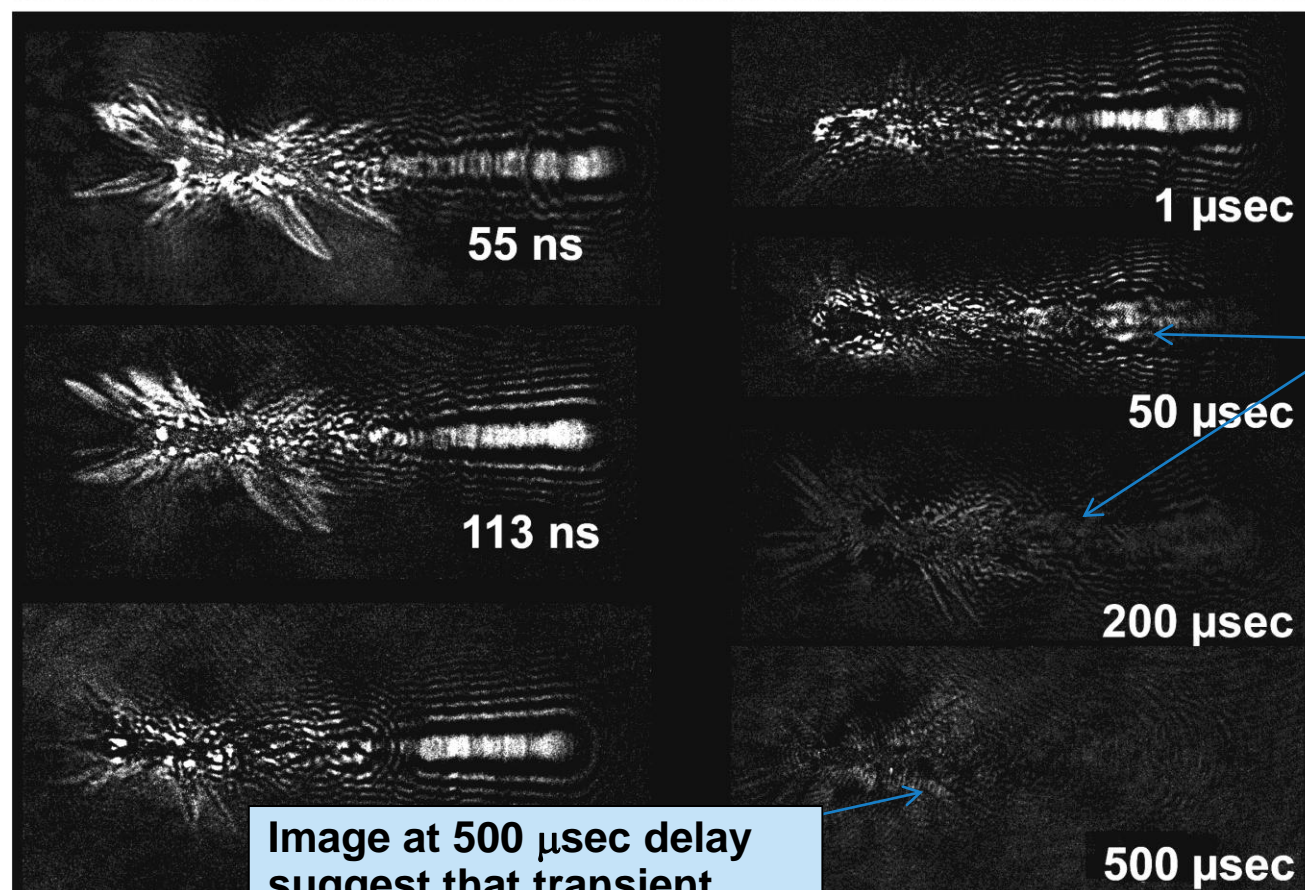
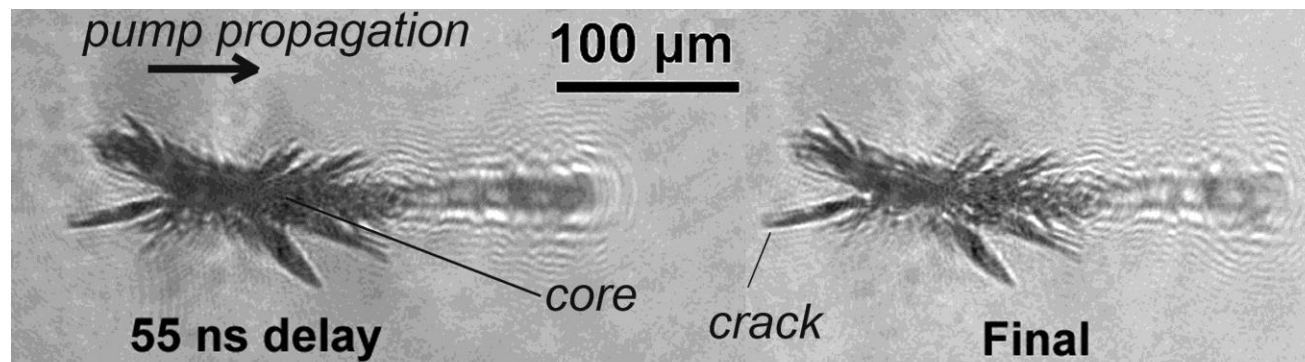


Image at 500 μsec delay suggest that transient absorption terminates

- Cracks and core region absorb light
- Absorption by cracks stops at ~ 300 ns
- The core region is also associated with a transient absorption for a much longer time, up to ~ 200 μs

Ratio TR images highlight the locations of the transient absorption

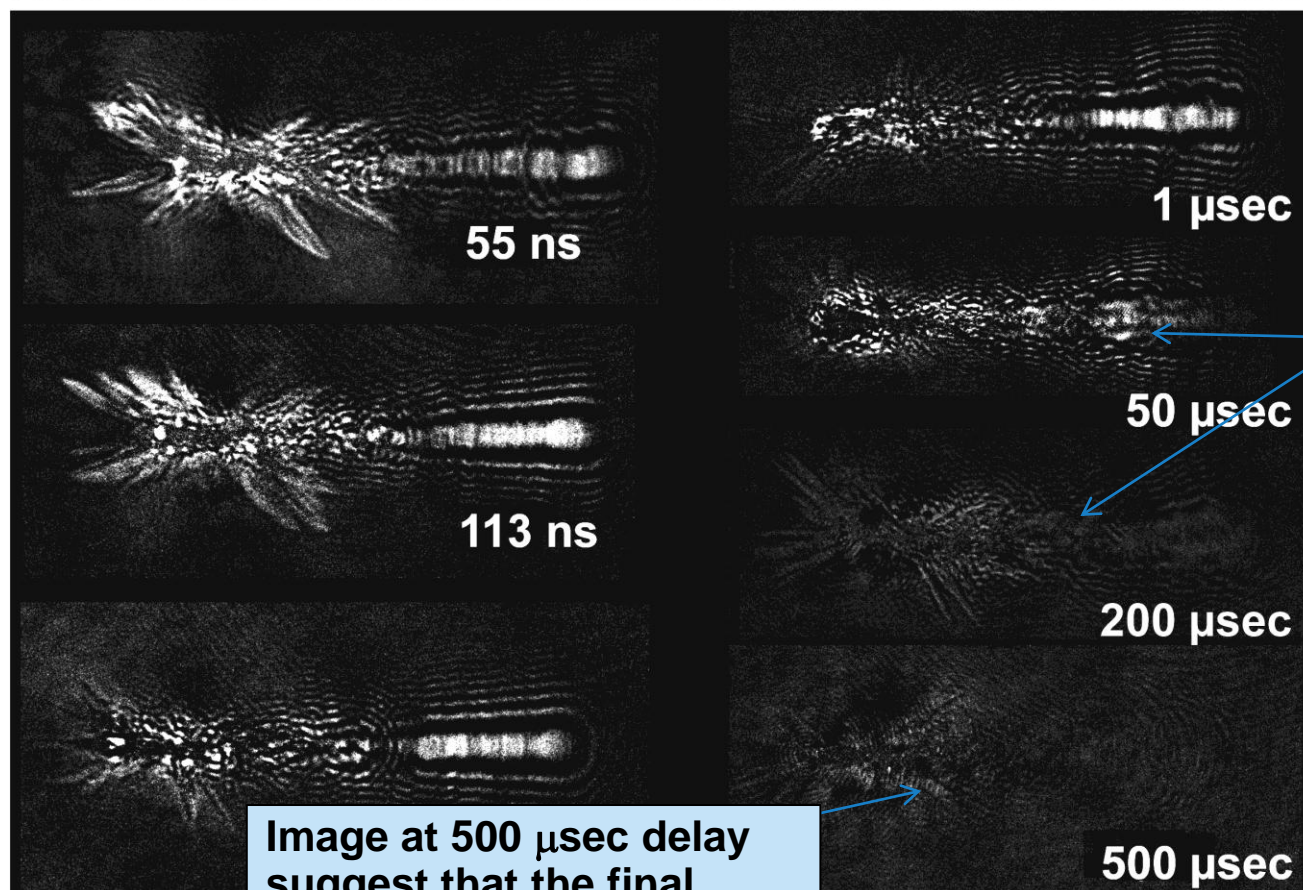
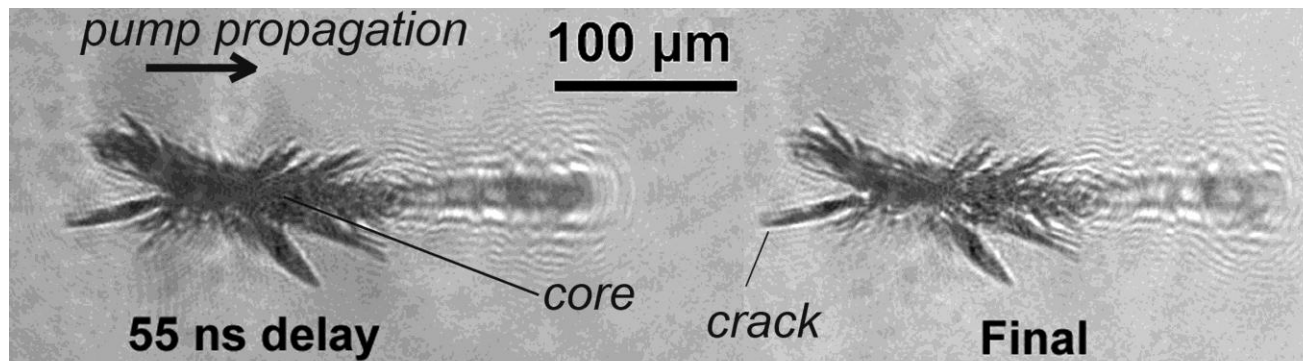


Image at 500 μsec delay suggest that the final state has been reached

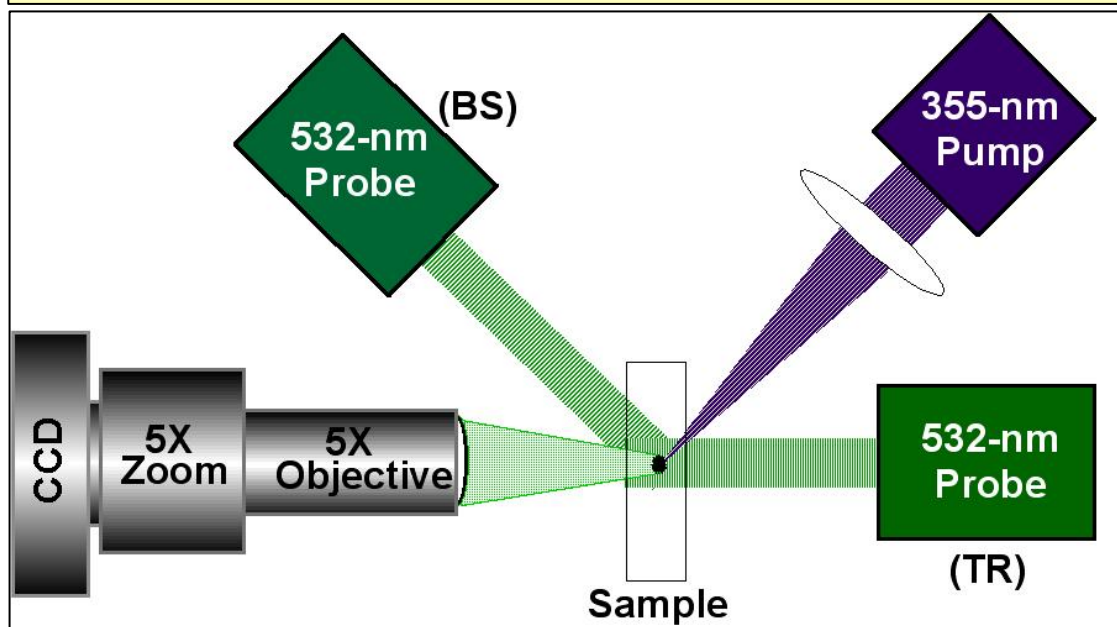
- Cracks and core region absorb light
- Absorption by cracks stops at ~ 300 ns
- The core region is also associated with a transient absorption for a much longer time, up to ~ 150 μs
- We postulate that the material in the core region is in a liquid or vapor phase at high $T^{1,2}$

^{1,2}Proc. SPIE 5273, 74 (2004) and
Proc. SPIE 6720, 672009 (2007)

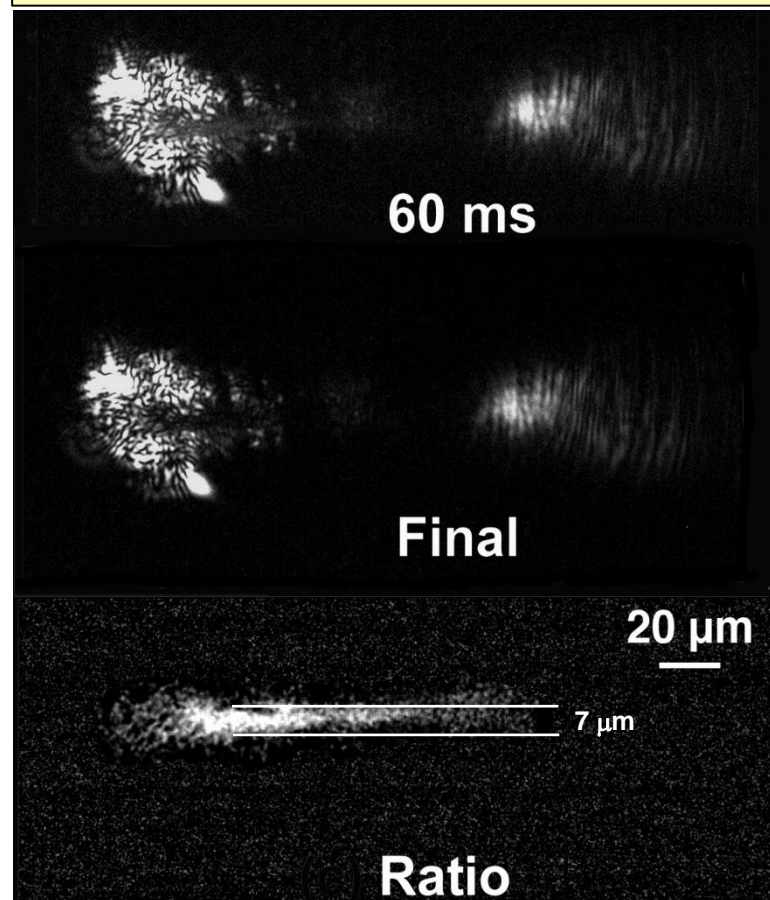
The last step in the damage process is returning of the “core” region to solid phase

Hypothesis: This phase change will lead to changes in the scattering properties of the material

Our imaging system can be re-configured to a back-scattering geometry (BS)



Ratio BS images highlight the locations of transient scattering



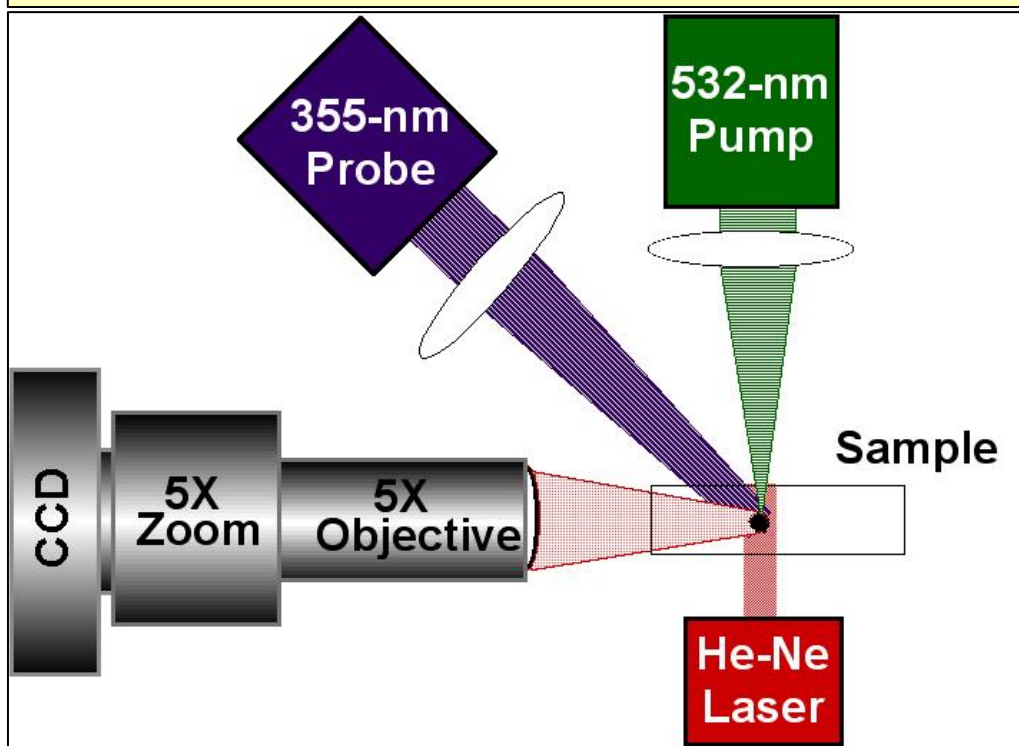
- This scattering effect may be due to micro-void formation by volume contraction during cooling of the material in liquid phase^{3,4}
- This effect terminates at about 70 msec delay

^{3,4}Phys. Rev. Lett. 97, 025502 (2006) and 100, 135502 (2008)

We use a pump and probe damage testing system to differentiate between the loss mechanisms

Transient images revealed changes in the absorption and/or scattering of the probe laser light incident upon the damaged volume

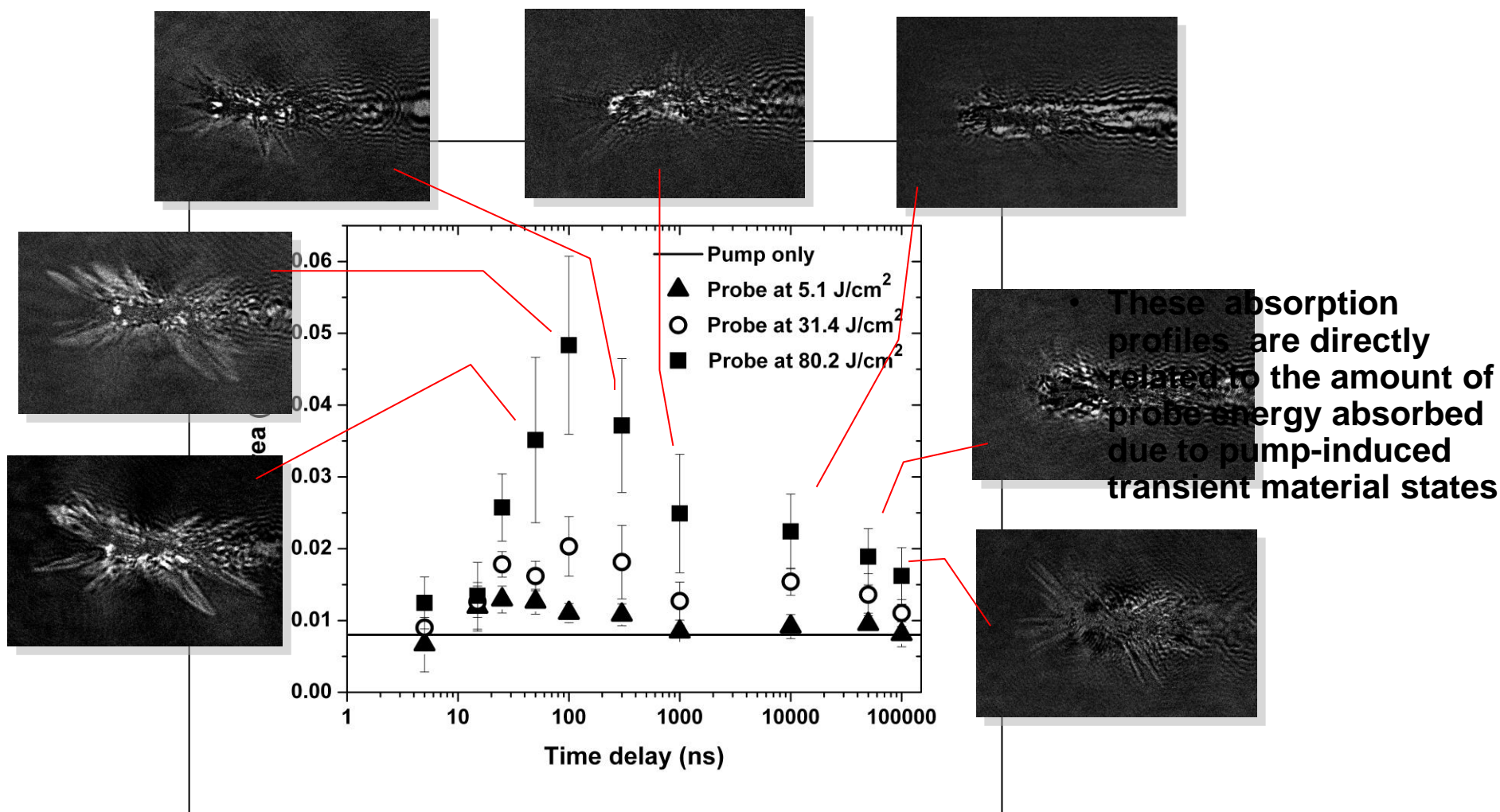
Pump and probe damage testing geometry



We indirectly monitor the transient absorption (not scattering) in the damaged region

- The presence of enhanced absorption by the host material due to the pump will lead to higher energy deposition by the probe pulse
- This effect will be manifested as a larger in size damage site from the combined exposure to both pump and probe pulses

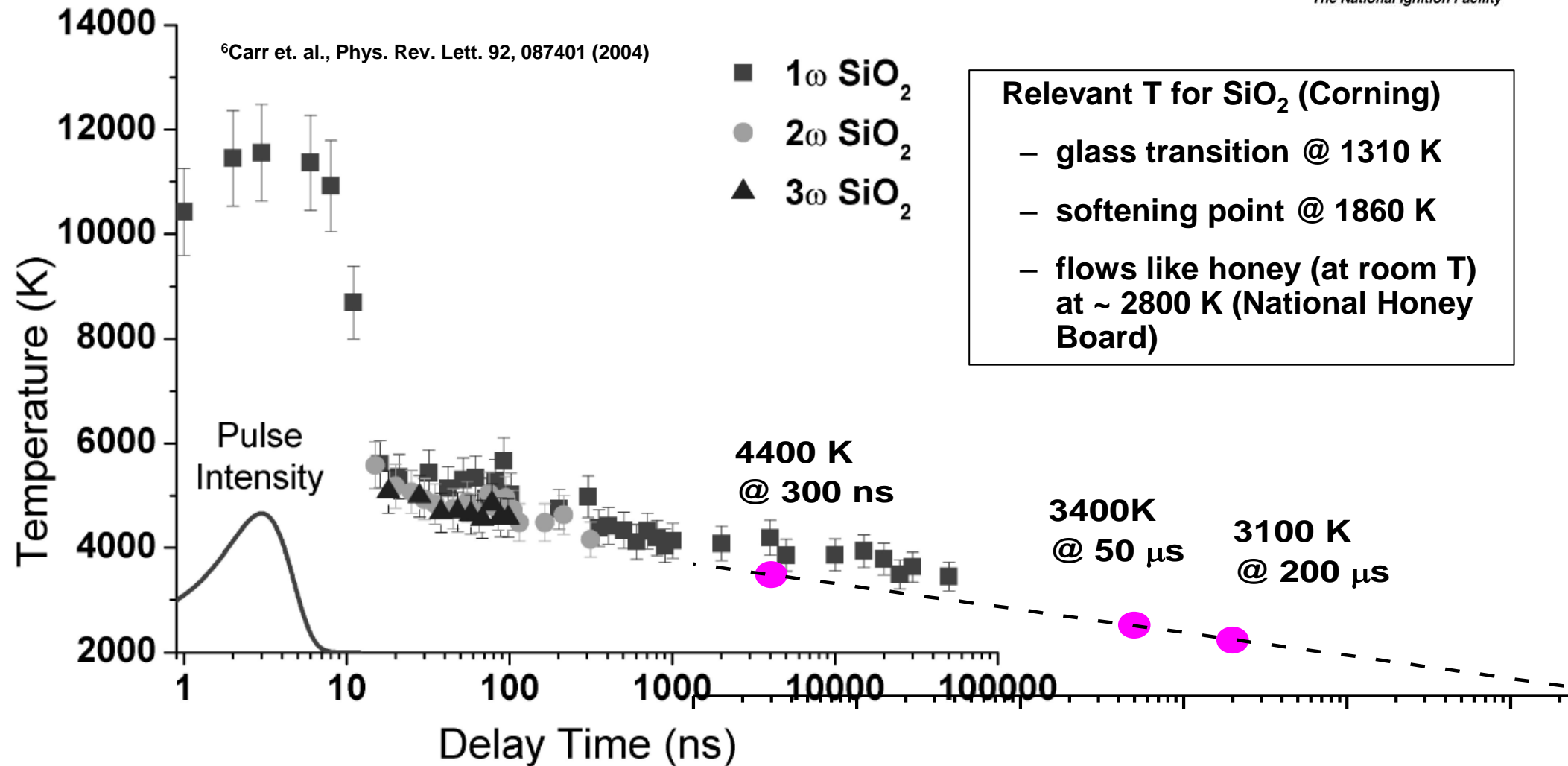
We compare the dynamic images of bulk damage with the pump-probe damage testing results⁵



⁵Negres et. al., Proc. SPIE 6720, 672019 (2007)

Combined results confirm the presence of transient absorption in the pump-induced modified material volume (cracks & “core” regions)

We extrapolate temperatures along the timeline based on the temporal behavior of the emission⁶ during a bulk damage event in SiO₂



Relevant T for SiO₂ (Corning)

- glass transition @ 1310 K
- softening point @ 1860 K
- flows like honey (at room T) at ~ 2800 K (National Honey Board)

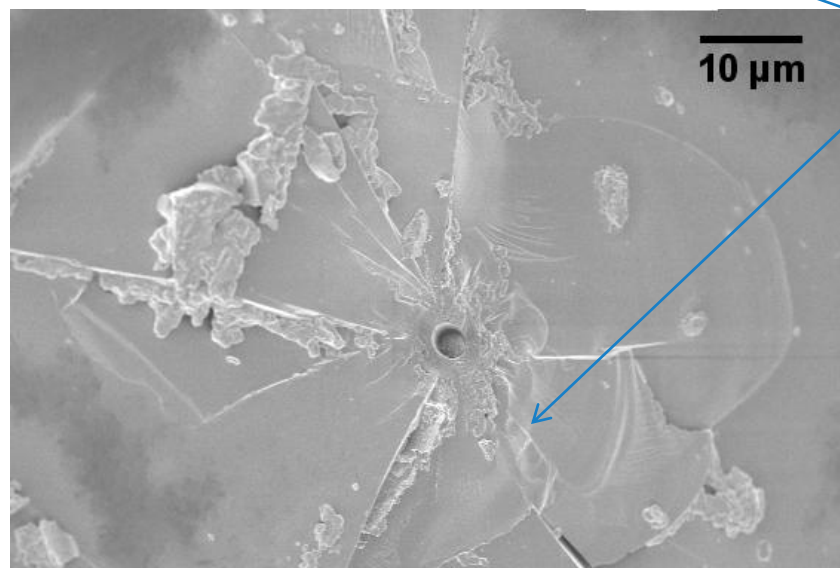
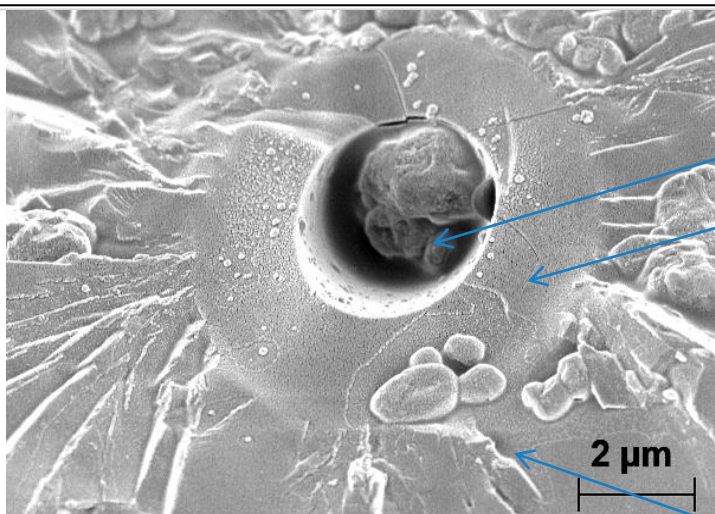
The return of the melted material to solid phase at ~70 ms (as suggested in BS images) and the estimated T are in excellent agreement with the softening point of SiO₂

- The transformation of silica at high T to a more absorptive material phase has been previously suggested^{7,8}

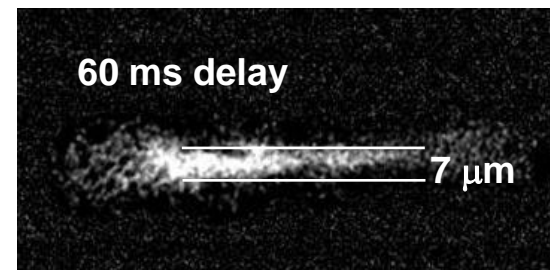
^{7,8}Phys. Rev. B 62, 8584 (2000) and
Proc. SPIE 6720, 672009 (2007)

We correlate previous observations to the microscopic structure of the bulk damage site

SEM images of the axial cross section of a bulk damage site in fused silica



- The core region is about 7 μm in diameter
 - contains a cavity ($\sim 3\text{--}4$ μm in diameter)
 - the outer ring is homogeneous suggesting that it was formed at a later time



- Mechanically damaged region (due to the shockwave propagation following the initial energy deposition) was formed earlier (at times shorter than 50 ns) and extends out to ~ 100 μm

Conclusions

- We have developed an experimental system capable of imaging bulk damage evolution with adequate spatial and temporal resolution
- The results reveal the salient behaviors associated with the material response during the cooling phase:
 - *The mechanically damaged region is forming at times shorter than 50 ns*
 - *A large population of defects is established in the cracked region and decays within 300 ns*
 - *There is a core region that remains in a high temperature, liquid-gas state and exhibits a strong transient absorption for about 200 μ s*
 - *The material returns to solid phase at ~70 ms delay after laser energy deposition*
- Future work is aimed at:
 - Resolving the shockwave physical dimensions and early dynamics
 - Formation dynamics and absorption characteristics of electronic excitation region
 - Employ hydrodynamic codes to model experimental observations and develop reliable theoretical models for this intermediate physical regime between cold materials and HED matter